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METHANATOR FUELED ENGINES FOR POLLUTION CONTROL

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16. Abstract

Comparison of a methanator fueled Otto-cycle engine is made with other methods proposed to control pollution due to automobile exhaust emissions. The comparison is made with respect to state of development, emission factors, capital cost, operational and maintenance costs, performance, operational limitations, and impact on the automotive industries. The methanator fueled Otto-cycle engine is projected to meet 1975 emission standards and operate at a lower relative total cost compared to the catalytic muffler system and to have low impact. Additional study is required for system development.

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SUMMARY

In situ methanation is one of the most promising approaches to meet the 1975 pollution standards. Comparison of the methanator fueled Otto cycle engine has been made with other proposed methods to meet the pollution standards such as:

a. Those developed for the Otto cycle engine in the inter-industry emission control program

b. The compressed natural gas (CNG) powered Otto cycle engine

c. The Wankel engine + exhaust reactor

d. The Rankine cycle steam engine

e. The Brayton cycle gas turbine

f. The Stirling cycle engine

g. The "Boston" car

h. The stratified charge Otto cycle engine + exhaust reactor

The comparison was made with respect to state of development, emission factors, capital cost, operational and maintenance costs, performance, operational limitations and impact on the automotive industries. The catalytic muffler was chosen as the most probable candidate the auto industry will use to meet the 1975 standards. Based on reasonable methanator program goals, the methanator fueled Otto cycle engine is projected to meet the 1975 standards and operate at a lower relative cost ($100/year) compared to the catalytic muffler system and have low impact.

Section I:

a. Pollutants From Present Engines.

Intracity and intercity travel is heavily dominated by internal combustion motor vehicles of the Otto cycle type. In 1968, 87% of intercity passenger miles was accounted for by private cars, 2-1/2% by motor coaches and a little over 9% by aircraft (1). In intracity transportation mass transit shares a greater percentage, however on the average the maximum never exceeds 35% and is often less; almost all the remainder is due to the automobile. (2).

Of the nearly 100 million combustion engine types in use, only about 0.5% are of the Diesel type while 99.5% are of the Otto cycle reciprocating piston type. (Even then the Diesel type is less of a noxious pollution problem than the Otto cycle type engine). These facts coupled with the fact that 40-70% of the total pollution in some cities is due to transportation modes. (3,4)* indicts the Otto cycle combustion engine as a major contributor to air pollution in the U.S. Typical concentrations of hydrocarbon (HC) carbon monoxide (CO), nitrogen oxides (NO_x) and particulate pollution in vehicular exhaust emissions are shown in Table I.

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*Authors' note: Reference 4 has been an invaluable aid in preparing this report.

TABLE 1. Standards and emissions for automobiles

		Hydro-carbons GM/Mi	CO GM/Mi	NO_x GM/Mi	Partic-ulates GM/Mi
Federal/California Standards	1975	.5/.5	11.0/12.0	.9/1.0	.1/ -
Federal Standards	1980	.25	4.7	.4	.03
*Urban Driving Conditions					
For Vehicles with no Exhaust Controls					
Gasoline — Automobiles		17.0	75	3.86	.364
Gasoline — Trucks		31.2	137	7.1	.68
Diesel Bus		12.4	5.4	20-14	10.0

*Subject to driving conditions and statistical variation

b. Current Emission Factors

Recognizing the inherent biological hazards to the population and environment and the nearly 6% annual increase in number of automobiles (3), California passed legislation in the 60's setting pollution standards which restrict the CO, HC, NO_x and particulate matter from automobiles, powerplants, and commerce. In Table I are listed the legal standards which restrict the emissions from vehicles set by the Federal government and the State of California for 1975 and projected for 1980 and as mentioned, the exhaust emissions in grams/mile for urban driving conditions for vehicles with no exhaust controls. As can be seen none of the Federal or California regulations for 1975 or later can be met with present unmodified engines.

c. Current Methods To Meet 1975 Standards

In this report we shall consider only the Federal and State of California legislation passed or proposed in 1975 or 1980 and the relation of a methanator fueled Otto cycle engine compared to some alternatives which attempt to meet these requirements and thus reduce the levels of pollution. These alternatives are those which the auto industry is presently considering as candidates or are those which may radically differ from the internal combustion reciprocating engine.

Choice of Comparisons to Methanator Fueled Otto-Cycle Engine

Those alternatives to which the methanator fueled automobile will be compared are:

a. Those developed for the Otto cycle engine in the inter-industry emission control program (IIEC) (7,8)

b. The compressed natural gas (CNG) fueled Otto cycle engine

c. The Wankel engine + exhaust reactor

d. The Rankine cycle steam engine

e. The Brayton cycle gas turbine

f. The Stirling cycle engine

g. The "Boston" car

h. The stratified charge Otto cycle engine + exhaust reactor

These engine alternatives may be categorized as internal combustion engines (ICE) and external combustion engines (ECE). The ICE's do not require that the internal energy of the chemical fuel be first converted to heat and then the heat, transferred to the working fluid.

As mentioned the Otto cycle reciprocating piston engine is the major type of ICE in use. In this engine the process of energy conversion to work is constantly interrupted and restarted often leading to incomplete combustion and increased pollution. In the ECE chemical energy is continuously converted to heat, the least recoverable form of energy, and subsequently, transfers a fraction of this energy to a working fluid which expands or contracts by heating, vaporization or cooling, condensation.

These alternatives and the methanator fueled ICE can be grouped in these categories as shown in Table 2.

TABLE 2. Engine types

ENGINE TYPES		
Internal Combustion Engines	Intermediate Type	External Combustion Engines
Inter-Industry Emission Control Program - Otto Cycle Compressed Natural Gas Fueled Otto Cycle Methanator Fueled Otto Cycle Wankel Engine with Exhaust Reactor Stratified Charge With Fuel Injection Otto Cycle Brayton Cycle Gas Turbine	"Boston" Car	Rankine Cycle Steam Engine Stirling Cycle Engine

The IIEC Program proposed three basic packages of emission control devices whose projected life time is 50,000 miles and which do not require extensive internal modification of existing engines (8).

I. Exhaust gas recirculation (EGR) plus a thermal manifold reactor

II. EGR with a Hydrocarbon (HC), Carbon monoxide (CO), catalytic reactor, spark retard and enriched carburation

III. EGR with dual catalytic reactors, one for HC-CO and a second for nitrogen oxides (NO_x), programmed ignition timing and enriched carburation.

The functions of these modifications are as follows:

The EGR system serves to dilute the inducted air/fuel charge with a portion of exhaust gas, thereby reducing peak combustion temperature and minimizing NO_x formation which increases with temperature.

The thermal reactor systems serves to combust exhaust hydrocarbons to CO_2 and H_2O by adding additional air to the exhaust and operates continuously at 1000°C (no appreciable NO_x should be produced). The HC-CO catalytic converter serves to combust HC and CO to CO_2 and H_2O by adding additional air to the exhaust and subsequently passing this mixture over a catalytic converter usually containing a platinum, silver, or chromium alloy on ceramic support typically operating at around 200-300°C. (3)

The NO_x catalytic converter precedes the HC-CO converter and reduces NO_x by oxidizing CO. The products that result are N_2 and CO_2. Operation is usually at 100-300°C and copper chromite type or copper oxide, cobalt oxide on alumina have been used (3,9,10).

The Wankel engine is basically an Otto cycle engine but replaces the reciprocating piston with a rotor which rotates eccentrically.

Fuel injection and special mixing by using electronic sensing and feedback can maintain optimum air feed settings for different driving conditions. A special stratified charge injection system and cylinder produces a rich fuel/air mixture near the spark plug and a lean fuel/air ratio elsewhere. These are used on ICE's.

In the Brayton cycle gas turbine, air is compressed, fuel injected and combustion occurs in an expander. Power is derived from the impulse of exhaust gases impinging on turbine blades.

The Boston car is a gasoline fueled reformer (ECE) which converts gasoline to H_2 and CO_2 which are then used as fuel for an ICE.

The Rankine cycle or steam engine is an ECE in which fuel is burned and heat transferred to steam (or in future designs an organic fluid) which vaporizes and condenses in a Rankine closed work cycle.

The Stirling engine is an ECE in which fuel is burned and heat transferred to air, H_2 or He which expands and contracts in a closed work cycle.

It should be noted that exhaust reactors could equally well be fitted on all of the different engines above; we will not consider these additional permutations and combinations in this report.

With respect to emissions these modes of combustion engines result in projected exhaust emissions as shown in Table 3.

d) Economic Impacts and Considerations

As can be seen from the table all of the proposed modifications meet or come close to the 1975 California or Federal Standards. It would be unfair to eliminate any of these alternatives based on emission standards alone. Rather the advantages of one alternative compared to another must be assessed on other bases. The criteria we have chosen for the comparison are as follows:

1. Availability with regard to a seven year period from 1973 to 1980.
    a) Development
    b) Impact on the automobile and accessory industries
        1) Dislocations in industries and the economy
            a. Manufacture
            b. Overhaul and service equipment
        2) Psychological resistance to change
2. Performance as an automobile
3. Costs
    a) Capital (initial cost)
    b) Maintenance
        1) Cost of major repairs
        2) Cost of transmission maintenance
        3) Minor cost of repairs, tune-up
        4) Cost of working fluids, oil, filters
    c) Fuel Costs

TABLE 3. Emissions from different engine types

Federal Standards 1975/1980 Engine Modification	HC (Gm/Mile) .5/.25	CO (Gm/Mile) 11.0/4.7	NO_x (Gm/Mile) .9/.4
IIEC - Otto Cycle (8) (All Modifications)	.82	7.1	.68
CNG Fueled Otto Cycle (19)*	.267**	4.12	.88
Wankel Engine (Unmodified/Modified with DuPont Exhaust Reactor) (13)	24.0/1.8	92.0/23.0	2.2/2.2
Ranking Cycle Steam Engine (14, 15, 16)	.013 - .4	.35 - 2.0	.25 - .6
Brayton Cycle Gas Turbine (17, 18)	.2 - .9	2 - 8	1.0 - 1.6
Stirling Cycle Engine (15, 17)	.006 - .1	.3 - 1.0	1.0 - 2.6
The "Boston" Car (20)	0.0	0.0	0.0 - .4
Stratified Charge Fuel Injection - (Texaco Process/ Ford Process + Exhaust Reactor) (11)	4.58/.15	9.62/4.3	1.74/.51
Methanator Fueled Otto Cycle Engine (19)***	.267	4.12	.883

*Average of Field Tests on Six Auto Types

**Less Methane (Methane is considered to have negligible reactivity with respect to smog formation (12))

***Data assumed similar to CNG Fueled Otto Cycle

4. Miscellaneous

a) Safety

b) Regional considerations

c) Operational limitations

Certain of the criteria are more difficult to assess than others. We have tried to include as much reference material as possible to support the comparison, however, it has been necessary also to estimate personally other information.

1. Availability (1973-1980)

Availability is dependent on the developmental stage of the powerplant as well as strongly dependent on the impact it has on the automobile industry and accessory industries. We are considering candidate powerplants which will be available in the next seven years from 1973-1980.

a) Engine Development

An ICE engine type such as the Otto cycle reciprocating piston engine is overwhelmingly the present developed and tested powerplant; turbines have also been developed but the Wankel engine has only recently been available for commercial testing. Of the ECE's the Rankine steam engine is the only one which has had large scale development and operational testing for nearly 70 years.

In toto the Otto cycle, turbine and steam engines are the best developed in the broad ICE, ECE categories.

b) Add-on Control Devices

Most additive control devices have been highly developed except stratified charge fuel injection and the "Boston" car. The catalytic muffler still has some minor developmental work necessary. With extended use the catalyst carriers still do not possess the desired mechanical properties and some break-up and attrition of the catalyst occurs. The NO_x catalytic muffler also presents some problems because under some operating conditions it may produce a biologically hazardous gas, ammonia. All catalytic systems require fuels developed which are relatively free from sulphur and lead. This will be discussed further later.

2. The Impact on the Auto Industry and Accessory Industries

a) Engines - Impact

In 1963 motor vehicle production alone accounted for 4.2% of the GNP, related services, tires, oil, batteries and accessories accounted for 4.1%, for a total of 8.3% of the GNP (21). In 1966 auto manufacture and related services accounted for between 10 and 15% of the GNP, and involved nearly a million business establishments (22,23). Consumer expenditures on auto depreciation, maintenance, gasoline, oil and insurance were $1000/household in 1965 or close to $60 billion dollars a year or 10% of personal income (22). Because business also uses automobile transportation and the transportation is a component of the cost of goods and services, consumer prices are indirectly affected by a change made in transportation. Therefore effects on just the auto industry have a wider effect on our whole economy. The impact of changing the engine and transmission in an automobile has a major effect on the manufacturing process. It is estimated that more than 30% of the automobile cost is due to the engine and transmission. Therefore such changes have a major effect on the auto industry and economy as a whole.

We will only consider impacts on the industry with regard to the three engine types considered developed most. Similarly, if required, other types of engines can easily be placed in the same argumentation presented for the developed engines, i.e., for the Otto cycle, turbine and steam engines. All impact effects are summarized later anticipated for each engine type.

The Steam Engine

The steam engine will not need a transmission, starter motor, carburetor, engine block cooling system, etc. but result in manufacture of heat exchanges, radiators, stainless steel tubing high-temperature lubricants, etc. (24). Because no extensive overhaul and service equipment for the steam engine is presently available a strong impact would occur which would change the service and maintenance industry requiring extensive retraining and refitting. Because actual thermal efficiencies of the steam engines presently are not equal to the Otto cycle engine and little cracking of petroleum stocks would be necessary it would also require change in the petroleum industry (25).

The Gas Turbine

Although the thermal efficiency can be as high as the Otto cycle engine and it is simpler mechanically and some overhaul and service techniques are developed, the gas turbine would also require a major change in the automobile manufacturing process (26). The turbine does not need a cooling system, carburetor or multiple spark ignition but does require a special high ratio gear reduction system and high temperature resistant alloys. The petroleum industry would also be effected because again certain refining techniques would not be required because low grade fuels may be used.

It would thus require a major cost in dollars and realignment of industry to mass produce steam or turbine engines. Psychologically there is inherent resistance to change; this combined with the cost and dislocations in the automobile manufacturing service industries alone could preclude mass production of the Rankine steam engines or turbine engines (however subsequent future developments or special needs may result in limited availability) (27). Thus as an alternative it is projected that the steam and turbine engines will only have restricted availability in the next ten years. Eventually with the fossil fuel reserves dwindling, electric propulsion nuclear, fusion, batteries and fuel cells as energy sources may become dominant (13,27,28).

b) Add-on Control Devices - Impact

Catalytic control systems require expansion in the catalyst industries. Approximately 240 million pounds of catalysts will be needed for the motor vehicles in the U.S. with an annual production of 120 million pounds. This quantity will impose loads on the metals industries and stimulate a metals recovery and reprocessing industry. However, the equipment and manufacturing processes are already existent to a high degree because the catalysts are similar to those in production for years to supply the needs of the chemical and petroleum industries. From a cost standpoint it is anticipated that catalyst production impact will only be about a tenth that of a change in engine type.

Stratified charge fuel injection will impose an additional impact because in addition to the exhaust reactor necessary to meet pollution standards it will require some redesign and refitting of the Otto-cycle engine with special cylinder heads and electronic fuel injection equipment.

The "Boston" car fuel conversion system may be also considered as an add-on. Because of the high pressure and temperatures necessary for operation the fuel conversion system is considered in the first estimate to have an impact between the catalytic muffler and steam engine.

The natural gas supply would have to be doubled to supply CNG as an automotive fuel. At the present supply rate the automobile would require 80% of our gas supply (29). This is difficult because supply void of automobile requirements already cannot meet demand and gas shortages have occurred. CNG as an add-on also has an impact on distribution centers. The present fuel distribution centers would have to be replaced by large compressor-supply depots (30). Thus CNG fueling would have major impacts on the petroleum industry which would have to convert to fuel oil gasification plants and the radically change the fuel distribution system.

3. Performance as an Automobile

In Table 4 are presented the projected performance characteristics for the various alternatives and their initial costs. All the alternatives represent reasonable performance levels.

4. Costs

In Tables 4, 5 and 6 are presented cost comparisons for the alternative methods.

Costs are summarized in Table 7.

5. Miscellaneous

a) Safety

Fuel Safety

There should be no problem with safety for the various engine types based on the Otto cycle, the steam or turbine engines with proper maintenance. It is premature to assess the other alternatives fully which are considered not developed far enough to be serious contenders. Generally, though, even hydrogen handling and materials technology are advanced far enough for normal safe operations (37). In the case of catastrophic

(Ref. 29,31,32,33,34)

TABLE 4. Engine performance and costs

Engine Type	Trans-mission	Overload Capacity H.P.	Parasitic Losses %	Rated H.P. to Deliver 100 H.P. at Wheels	Max. Brake Thermal Eff. (at Full Ld.)	Max. Net Energy Conver-sion %	Total Wt Lb	Total Cost $	Δ Cost Over Gasoline Engine
Gasoline 4 Stroke Otto Cycle	3 Speed Auto or Manual	0	33% (Trans-mission, etc.)	150	27-30%	19	750	750	0
Gasoline + Exhaust Reactor	"	0	37	150	23-26%	15	825	1050	300
Methanator Fueled Otto Cycle	"	0	35	175	26-29%	18	900	1145	395
Comp. Nat. Gas Fuel Otto Cycle	"	0	33	175	28-31%	20	1000	1100	350
Stratified Charge Gasoline + Exhaust Reactor	"	0	∿33	150	30-32	21	850	1100	350
Wankel Engine + Exhaust Reactor	"	0	∿25	150	20-23	19	335	900	150
Rankine Cycle Steam Engine	Differ-ential	25	28	110	18-24%	14	715	925	175
"Boston Car"	3 speed	0	35	175	21-24	16	1000	1400	650
Stirling Engine	2 speed	0	40	110	32-38	22	1100	1990	1240
Gas Turbine	Diff.	0	25	110	20-26	17	400	1500	750

(Ref. 19,35) TABLE 5. Engine fuel costs

Engine Type	Fuel Consumption (10 Yr Total)		
	Miles Per Gallon	Cost 1970 Dollars	Cost Difference From Gasoline Eng.
Gasoline 4 Stroke Otto Cycle	13	2560	0
Otto Cycle Gasoline + Exhaust Reactor	11	3025	+ 465
Methanator Fueled Otto Cycle	13	2560	0
Comp. Nat. Gas Fuel Otto Cycle	14	2380	- 180
Stratified Charge Gasoline + Exhaust Reactor	15	2210	- 350
Wankel Engine + Exhaust Reactor	11	3025	+ 465
Rankine Cycle Steam Engine	12	2770	+ 210
"Boston" Car	11	3025	+ 465
Stirling Engine	15	2210	- 350
Gas Turbine	10	3320	+ 760

(Ref. 3,8,19,28,30,36)

TABLE 6. Maintenance costs

Engine Type	Major Repairs $	Trans-mission $	Minor Repairs (Tune-Up)	Working Fluids $	Total $	Cost Difference From Gasoline Engine
	10 Year Maintenance Costs 1970 Dollars					
Gasoline 4 Stroke Otto Cycle	500	200	800	280	1780	0
Gasoline + Exhaust Reactor	500	200	1300	330	2330	+ 550
Methanator Fueled Otto Cycle	0*	200	900	100	1200	- 580
Comp. Nat. Gas Fuel Otto Cycle	0*	200	400	100	700	-1080
Stratified Charge Gasoline + Exhaust Reactor	500	200	1150	280	2130	+ 350
Wankel Engine + Exhaust Reactor	500	200	1020	280	2000	+ 220
Rankine Cycle Steam Engine	600	50	400	400	1450	- 330
"Boston" Car	500	200	800	100	1600	- 180
Stirling Engine	500	150	200	300	1150	- 630
Gas Turbine	300	150	400	100	950	- 830

*Engine Life 200,000 to 250,000 miles. Private Communication, Pacific Lighting Co., Los Angeles, Calif.

TABLE 7. Relative costs

$\$\Delta\%$ of Unmodified Otto Cycle

Method	Δ Total*	% Change
Unmodified Otto Cycle Engine	$ 0	0%
Otto Cycle + EGR + Catalytic Reactors	$1375	∿ +25%
CNG Fueled Otto Cycle Engine	$-840	∿ -15%
Wankel Engine + Exhaust Reactor	$ 865	∿ +15%
Rankine Cycle Steam Engine	$ +90	∿ + 2%
Brayton Cycle Gas Turbine	$ 830	∿ +16%
Stirling Cycle Engine	$ 508	∿ +10%
The "Boston" Car	$1065	∿ +20%
Stratified Charge Fuel Injection + Exhaust Reactor	$+420	∿ + 8%
Methanator Fueled Otto Cycle	$-105	∿ - 2%

*Includes +20% interest on initial cost increment above Otto Cycle Engine cost.

failure, all fuels are potential hazards regardless of the engine type. Although some differences exist in ignition properties it is considered that the major potential danger is the quantity of fuel and that all alternatives are about equal in this regard.

b) Operational Limitations

Fuels Limitations

Low sulphur content fuels are desired with respect to emission of SO_2 from an air quality standpoint (38). Present fuel refinery catalysts are subject to sulphur poisoning and sulphur has been removed prior to production of the fuels used in all the engine types mentioned. Therefore, development of sulphur free fuel does not present a major problem. Although somewhat controversial with respect to its air pollution dangers, low lead is also desired with respect to air pollution (lead poisoning, a cumulative poison). Lead may also contribute to increased hydrocarbon exhaust emission (39). Most control device operation is also deleteriously affected by lead compounds (40). This limitation however is severe for catalytic controlled devices such as the methanator or catalytic muffler and therefore for increased operation lifetime (50,000 miles) lead compounds must be eliminated from the fuel for these options. Lead free fuels are now available and have been requested by the auto industry; the cost of lead free gasoline will be 0.5-2¢ per gallon above its present cost due to a change in refinery processing (29).

CNG as a fuel limits the range of operation of an automobile. The range of fleet cars which are now in operation is only 100 miles/500 ft^3 of gas (a two cylinder system (30). Either more frequent fuelings must occur or the additional complication of liquified gases used.

Working Fluids Limitations

Only the steam engine and methanator fueled Otto-cycle engine require special fluid additives with respect to regional climatic considerations. For the steam engine, freezing conditions pose a serious limitation. The water supply for the steam boilers needs protection from freezing. At present there is no known antifreeze which can be used which also survives the high temperatures in the boiler (41). (Organic working fluids such as thiophene may solve this problem but are still in the developmental stages.) Thus the steam engine operation will be limited by seasonal conditions in some geographical areas.

6. Benefits Evaluation - Summary

Catalytic Muffler

Advantages

1. The catalytic muffler and recirculation system is available and highly developed.
2. The system can be installed in existing automobiles and requires no significant changes in engine design.
3. The system will result in relatively low overall impact in the auto, chemical, and petroleum industries.

Disadvantages

1. An average increase in cost of +25% over a ten year period is required over existing unmodified engines resulting from installation, operation, and maintenance of the engine and exhaust control devices.
2. Some catalyst development work is still indicated.

CNG Fueled Otto-cycle

Advantages

1. CNG fueled vehicles are available and have been tested in fleet operations.
2. CNG fueled vehicles require no extensive changes in engine design and should result in low impact in the auto industry.
3. CNG fueled vehicles have lower total costs (-15%) compared to an unmodified Otto-cycle engine.

Disadvantages

1. Major impacts will occur in the gas and petroleum industries due to gas shortages and a change in fuel distribution centers.
2. Range of operation is only 100 miles for the present system.

Wankel Engine-Exhaust Reactor

Advantages

1. Lower engine maintenance costs compared to the Otto-cycle engine are anticipated.

Disadvantages

1. Wankel engines are not considered a well proven engine and may require further development.

2. Major impact would occur in the auto industry because retooling would be required to produce the radically different engine design.

3. A higher average total cost (+20%) would be incurred compared to an unmodified Otto-cycle engine.

Rankine Cycle Steam Engine

Advantages

1. Steam engines have had extensive development.

2. Average total costs are about equivalent (+2%) to an unmodified Otto-cycle engine.

Disadvantages

1. Thermodynamic efficiency and fuel utilization is low.

2. Major impact will occur in the auto industry because of the radically different engine design and the required retooling.

3. Operation is limited to warmer climates.

Brayton Turbine Engine

Advantages

1. Turbine engines have been developed and tested in the aviation industry and limited development occurred in the auto industry.

Disadvantages

1. Major impact would occur in the auto industry because of the engine's radically different design and required retooling.

2. The turbine engine has a higher total cost (+15%), compared to the unmodified Otto-cycle engine.

Stirling Engine

Advantages

1. The Stirling engine has a potentially high thermodynamic efficiency and fuel utilization.

Disadvantages

1. The Stirling engine has not had extensive development and testing.
2. Major impact will occur in the auto industry due to its radically different design.
3. A higher average total cost (+10%) is indicated compared to an unmodified Otto-cycle engine.

The "Boston" Car

Advantages

1. The fuel conversion "Boston" car does not require major changes in internal engine design and will result in a low impact in the auto industry and fuel distribution industry.

Disadvantages

1. The "Boston" car has not had extensive development and testing.
2. It is a hybrid system and loses some thermal efficiency.
3. High temperatures and pressures necessary for converter manufacture operation will result in a moderate impact on the special materials and fabrication industries.
4. A higher average total cost (+20%) is indicated compared to an unmodified Otto-cycle engine.

Stratified Charge Fuel Injection - Exhaust Reactor

Advantages

1. Moderate impact will occur in the auto industry due to engine design changes.
2. Potentially higher fuel efficiency is indicated.

Disadvantages

1. The system has not been fully developed and tested.
2. A higher total cost is anticipated (+8%) compared to an unmodified Otto-cycle engine.

Section II:

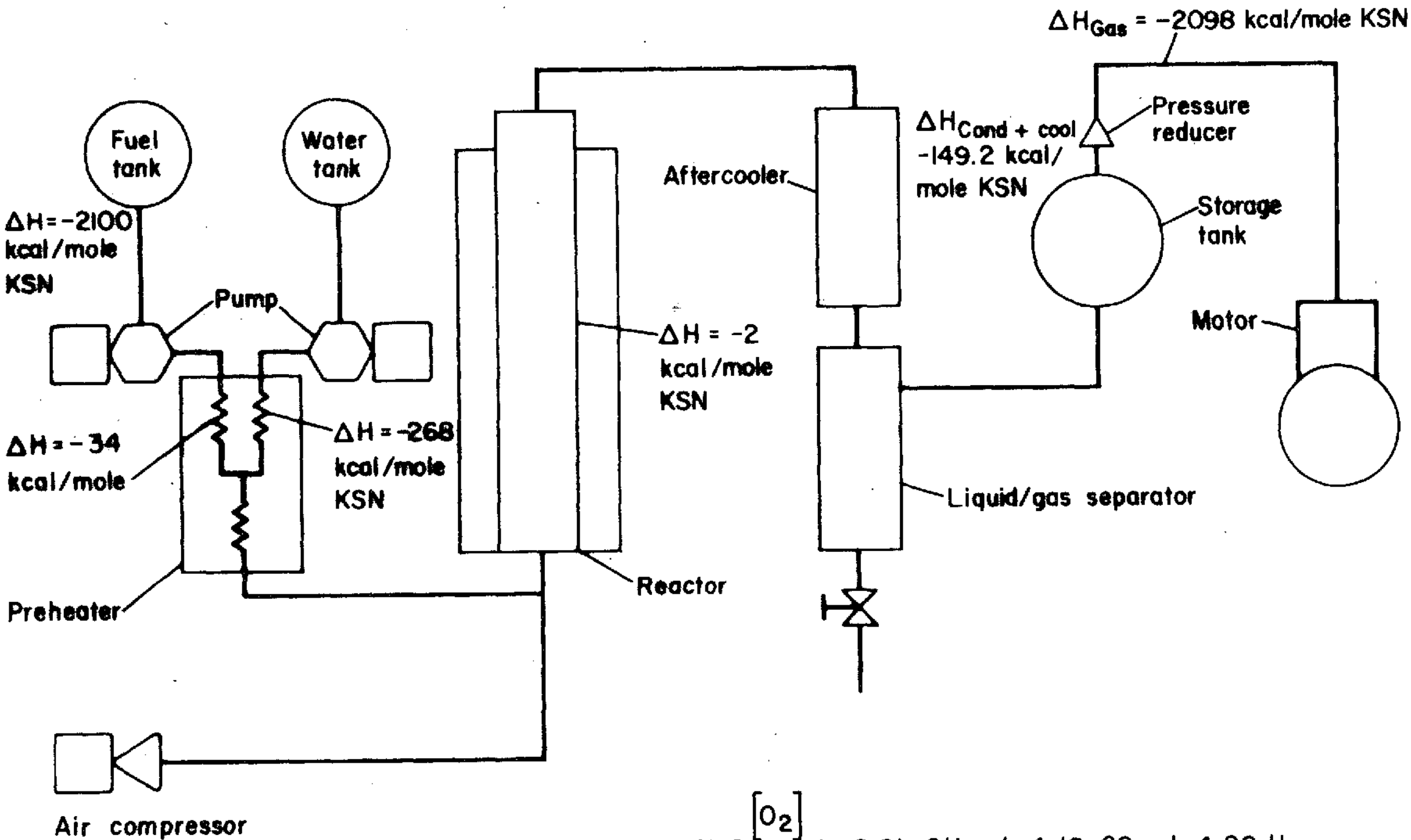
a) Ames Methanator Fueled Otto-cycle Engine

General Description and Operation

The Ames bench scale methanator fueled Otto-cycle engine (12 H.P.) is shown in the schematic in figure 1. Rough schematics for automobile application are shown in figures 2 and 3. A list of essential equipment is shown in Table 8 along with estimates on cost.

The system for automotive service will be a dual fuel system somewhat similar to that used by Pacific Lighting Service in its fleet operations (19,30). In this dual fuel system only a simple switch is used by the driver to convert from gasoline to compressed gas fuels. A venturi mixed is used to mix the fuel with air before injection into the engine.

The methanator reactor will provide the source of gas to the venturi. The methanator will consist of storage tanks for gasoline and water the reactants for the methanator, pumps to meter the



$$\text{Reaction}\quad C_{13}H_{27} + 8.40\ H_2O \xrightarrow{[O_2]} 8.81\ CH_4 + 4.19\ CO_2 + 4.28\ H_2$$

Fig. 1. Bench scale methanator system

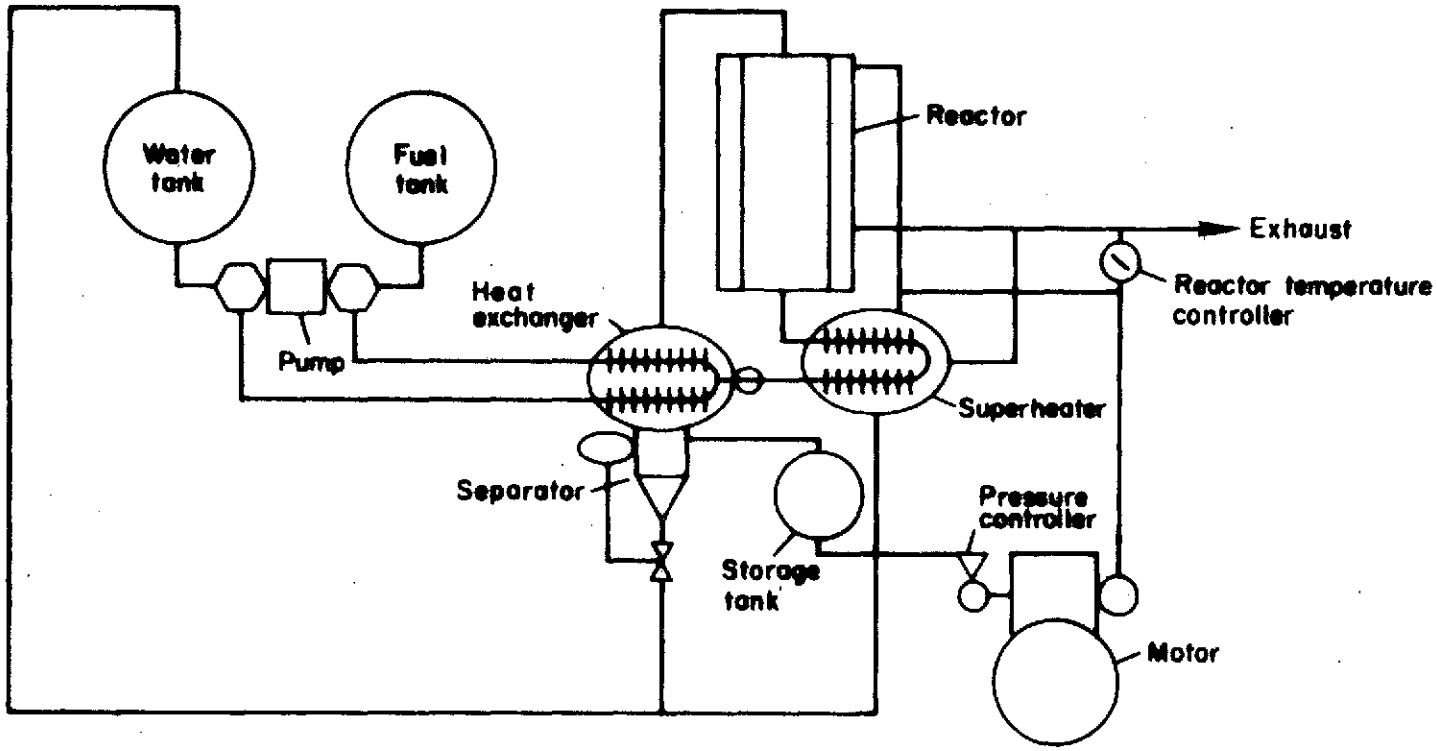


Fig. 2. Methanator schematic for automobile

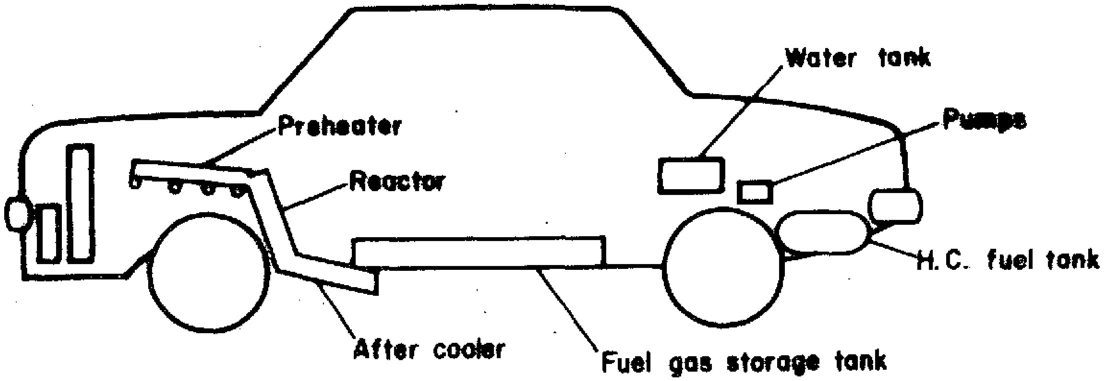


Fig. 3. Auto methanator system

TABLE 8

Cost for Methanation System for Automotive Service

Item	Possible Structure	Estimated Cost
Water Tank	Polyester-Fiberglass	$15.00
Fuel Tank	Same c [illegible] el	10.00
Fuel/Water Pump	Nylon-Brass	30.00
Heat Exchanger/Separator	Stainless Steel	50.00
Fuel Storage Tank	Steel/Aluminum	20.00
Superheater	Stainless Steel	25.00
Pressure Controller	Aluminum	10.00
Reactor Temperature Regulator	Steel	5.00
Reactor	Stainless Steel	40.00
Catalyst		80.00
Venturi Mixer		70.00
Dual Fuel Attachment		40.00
	Total	$395.00

proper reactant feed composition, feed preheaters to convert the liquid reactants to vapors, the catalyst and reactor, a fuel storage tank as a buffer fuel reserve, and a pressure regulator and controller.

Startup

Startup will consist of running the engine initially on gasoline until sufficient temperatures are reached in the exhaust heat exchanger reactor to vaporize the liquid reactants and provide sufficient temperatures for reaction. Gaseous product fuel is accumulated in the fuel reserve tank until a set operating pressure. When this is reached gasoline fuel will be shut to the engine and gaseous fuels used.

Cruising

Feed rates to the reactor will be automatically controlled dependent on a set pressure level in the reserve tank. Unreacted water will be condensed in an aftercooler and recycled to the water storage tank.

No novel control problems requiring special devices are foreseen.

b) Economic Impacts and Considerations

1. Availability

a) Development

A methanator fueled Otto-cycle engine (12 H.P.) has been developed and run successfully. Further development work with respect to catalyst lifetime is in progress. Along these lines industry has a major developmental program to produce similar systems for fuel oil gasification in the next five years. Construction of plants is already in progress and the technology considered advanced.

2. Impact on the Auto and Accessory Industries

The methanator fueled Otto-cycle engine is a fuel conversion system which does not require changes in internal engine design; therefore, low impact in the auto industry results. It also uses gasoline as fuel; therefore, has a low impact on the petroleum and fuel distribution industry and a low impact on the gas industry. Since it is a catalyst system it will have a similar effect on the catalyst industry as mentioned for the catalytic muffler; however, this effect is considered an order of magnitude lower compared to that resulting from changes in engine design.

3. Performance as an Automobile

In Table 4 are presented the projected performance characteristics for the methanator fueled Otto-cycle engine. It represents a reasonable performance level.

4. Costs

In Tables 4, 5 and 6 are presented a cost comparison for the methanator fueled Otto-cycle. Costs are summarized in Table 7.

5. Miscellaneous

a) Safety

Fuel Safety

There should be no additional safety problems than those mentioned for the other methods described due to the quantity of fuel. Methane fueled cars in fleet operations have not experienced hazardous incidents (19,30). The methanator reactor should not pose any major safety problem. (Steam reforming technology is well developed (37,42)). Hydrogen or methane are also not available in large quantities at any instant in time. If the catalyst reactivity remains the same as now and the present methanator design using the dual fuel system is the same we estimate less than a cubic foot of H_2 or CH_4 would be available as fuel in a catastrophic failure. CH_4 has a higher ignition temperature than hydrocarbon fuels such as gasoline (650°C-300°C). Both H_2 and CH_4 are lighter than gasoline fumes and lend to disperse more rapidly rather than settling close to the surface where an ignition source is likely to be located (28,30,37,43).

b) Operational Limitations

Fuels Limitations

Higher humidity will occur in methanator fuel product. NO_x exhausts seem to be affected by the humidity in the air (44). This may be due to the increased humidity or lowering of the absolute pressure or some other undetermined effect. The NO_x concentration decreases with increased humidity or pressure (44). The methanator should have a greater humidity in the fuel air mixture than intake air but this is considered of negligible benefit. The Ni methanator catalyst may be subject to sulphur poisoning (mainly due to sulphur in the gasoline or even in the intake air in heavily polluted industrial areas). Generally high grade fuels such as gasoline and others have low sulphur contents because the process cracking catalysts are also sulphur sensitive and therefore sulphur has been removed from stocks before they are upgraded to gasoline. Some Ni methanation catalysts promoted with copper and chromiun oxides are available which can be operated in the presence of small quantities of sulphur of about 3ppm such as a Japan Gasoline Co. catalyst (45,46). The worse concentration of SO_2 and H_2S (H_2S only has a short lifetime in the atmosphere and is oxidized to SO_2 in a few hours or days) in some cities like New York can reach levels of 1 to 1.5 ppb on occasion (47); therefore, it is considered that sulphur compounds in ambient air are not present to have a major effect.

Working Fluids Limitations

The methanator fueled Otto cycle engine will require antifreeze be added to the water reactant. This antifreeze is expected to be alcohol and to be used as a source of fuel in the reactor resulting in negligible increase in cost.

6. Technology Applications

Methanation can be applied equally to fuel other power sources so that pollution is reduced (Table 9). Fuel gas provides presently 30% of the fuel requirement for the nation. Shortages have been

TABLE 9

Reduction in Pollutants for Stationary Combustion Sources vs. Fuel Type

Emmision Factors for Various Fuel Types						
	Power Plant (a)		% Reduction	Domestic Heating (a)		% Reduction
Pollutant	Fuel Oil	Methane		Fuel Oil	Methane	
Aldehydes	0.6	0.114	81.0	2.0	0.0	100
CO	0.04	0.0	100	2.0	0.045	97.7
Hydro-carbons	3.2	0.0	100	3.0	0.0	100
NO_x	104	44.7	57	12.0	13.3	-10.8
SO_x	159.4	0.045	99.9	159.0	0.045	99.7
Particulate	10	1.72	82.8	8.0	2.18	65.0

(a) Factors compiled by the U.S. Air Pollution Control Agency. Factor = # LB Pollutant/1000 Gal. 2% Sulfur, API °35 Oil or BTU Equivalent.

evident in the recent past. It is projected (Figure 4) that rising demands for gaseous fuel and declining supplies will result in cost increasing 3-5 times the present cost (48,49). Methanation is a process which can convert fuel oil to gas to meet the increased demand; its technology is also evident as one of the important process steps in coal gasification such as the Pittsburgh Energy Research Center's "Synthane" coal gasification process (50). A methanation type process has also been used to produce hydrocarbon fueled fuel cells (51). Thus, besides auto pollution abatement, methanator technology is important in complementing energy fuel supply and powerplant pollution control.

7. Benefits Analysis-Summary

Advantages

1. The methanator fueled Otto-cycle engine requires little change in the existing automobile and results in low overall impact on the auto, chemical and petroleum industries.
2. It uses existing fuel distribution centers.
3. Its technology development can have spin off with regard to providing alternate sources of gas supply and control of pollution from stationary powerplant sources.
4. It has a relatively lower average total cost (-2%) compared to an unmodified Otto-cycle engine.
5. Advanced states of technology exist in related industry.

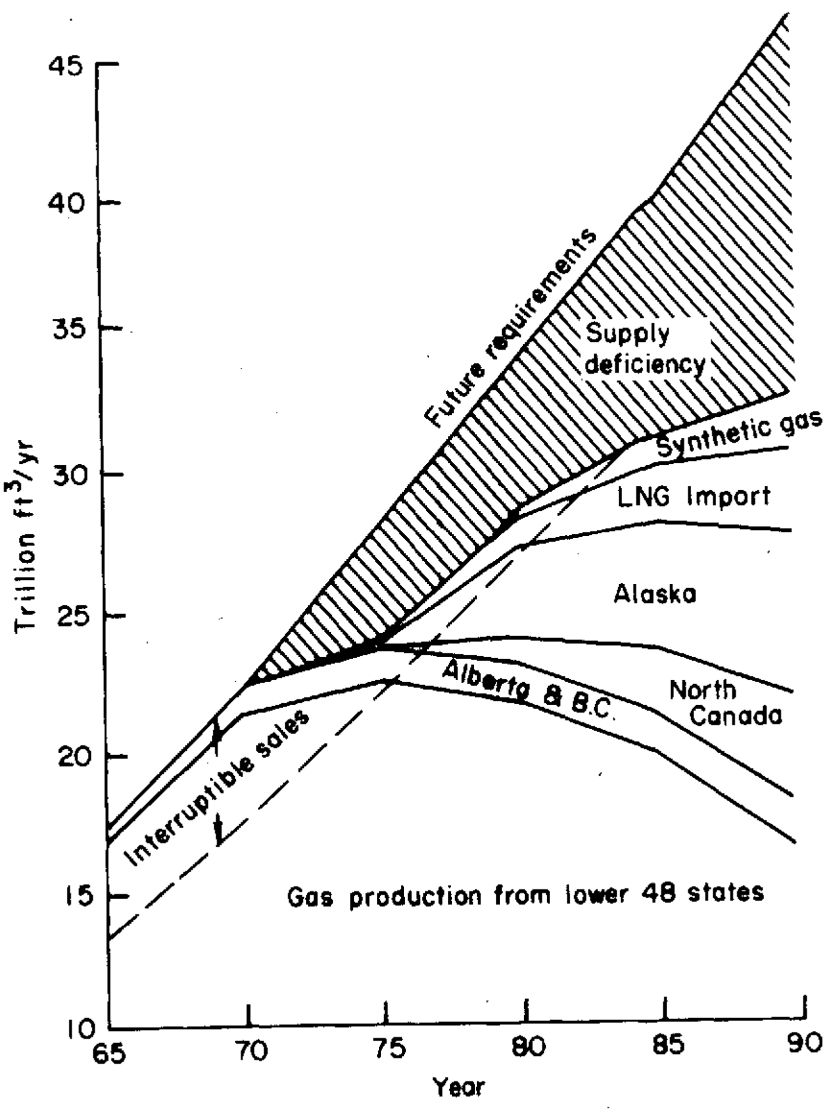


Fig. 4. Projected gas supply and demand

Disadvantages

1. Some additional development work in catalyst life extensions and design is warranted.

Section III:

a) Selection of the Most Probable Control Method Industry Will Select to Meet 1975 Pollution Standards

The most probable methods to be used on the dominate engine type, the Otto cycle engine (29), which industry is anticipated to use for 1975 pollution control standards are EGR and NO_x, HC-CO catalytic reactors (8,28,31,32). The subsequent choice will then be limited to a comparison between the methanator fueled Otto cycle engine and the catalytic exhaust modified Otto cycle engine.

b) Comparison of Methanator System to Industrial Candidate System

From a study of proposed methods for meeting the 1975 standards for automotive emissions the methanator fueled vehicle has almost a total 25% cost advantage over the catalytic exhaust system. This amounts to close to a $100 savings a year.

The reason the methanator fueled engines total cost is less depends primarily on maintenance costs. Methane fueled engines produce practically no particulates. Spark plug performance lasts greater than 5 times that on gasoline engines, engine oil lasts 3 to 4 times that of gasoline. Scale and gum buildup inside the combustion chamber and engine cylinders are less resulting in less frequent engine overhaul (engine lifetimes have been reported to be 200,000-250,000 miles). The exhaust system lasts longer due to less corrosive and particulate materials produced (19,28,30,52). Beside low impact in engine designs, using unleaded gasoline as starting fuel for both methanator and catalytic muffler the methanator should minimize impact on the petroleum and petroleum distribution network. Therefore, the two methods are comparable in this respect. Fabribation and installation of the methanator converter should be comparable to the catalytic muffler.

c) Conclusion

Though process development problems may still exist for both the catalytic muffler exhaust and methanator, the methanator fueled concept is a valuable investment which can cut pollution while reducing automotive operating costs, without major impact on the existing Otto cycle engine or petroleum refining and distribution systems. Alternative methods to solve the emission problems have been discounted in the next seven years as impractical because of an adverse impact on the auto industry (even though the steam and turbine engines may be increasingly competitive in the future.)

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